

## **2 OIL AND GAS EXPLORATION AND DRILLING TECHNOLOGY**

A variety of technologies are employed in the oil and gas industry to identify oil and gas reserves, to access those reserves, and to extract and deliver the products. The following subsections provide an overview of current technologies employed in oil and gas exploration and drilling.

### **2.1 OIL AND GAS EXPLORATION**

The exploration for oil and gas, which may be quite time- and effort-intensive and rely on the collection and detailed analyses of extensive geologic information, involves a number of activities, including the following:

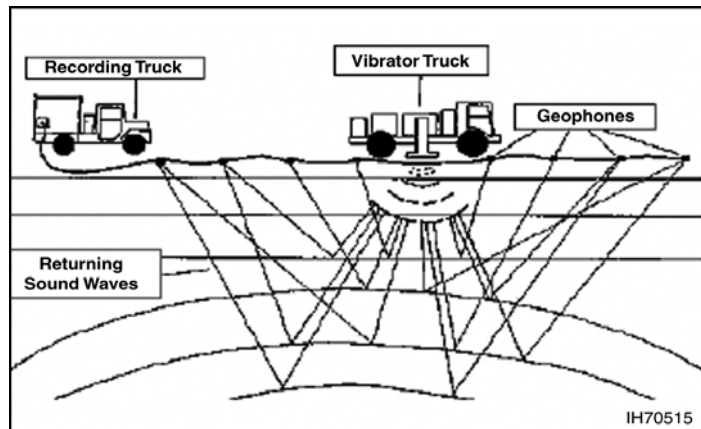
- Surveying and mapping surface and subsurface geologic features with techniques such as seismic reflection to identify areas (called hydrocarbon traps) where oil and gas may have accumulated;
- Determining a geologic formation's potential for containing commercial quantities of economically producible oil and/or gas;
- Identifying the best locations to drill an exploratory well to test the hydrocarbon traps;
- Drilling exploration and delineation wells to determine where hydrocarbons are present and to measure the area and thickness of the oil- and/or gas-bearing reservoir or reservoirs;
- Logging and coring wells to measure the permeability, porosity, and other properties of the geologic formation(s) encountered; and
- Completing construction of wells and site facilities deemed capable of producing commercial quantities of oil and/or gas.

While past surveying and mapping activities employed invasive techniques that included explosive seismic profiling and extensive drilling to map and locate potential reservoirs, modern exploration involves the use of non-explosive reflection seismic profiling, together with seismic imaging software and computers, to interpret geological and geophysical data more completely and to manage, visualize, and evaluate greater amounts of data more quickly and efficiently. Reflection seismic profiling transmits acoustic vibrations (seismic waves) underground. As these waves travel through different rock layers, some are reflected backward by the different subsurface layers to an array of receiving (detecting) geophones (or hydrophones, if in water). These reflections off of subsurface layers are then used to generate multidimensional representations of the subsurface.

### 2.1.1 Onshore Seismology

In practice, using seismology for exploring onshore areas involves artificially creating seismic waves, the reflections of which are then picked up by sensitive pieces of equipment called geophones embedded in the ground or placed on the ground surface (Figure 2.1). The data picked up by these geophones are then transmitted to a seismic recording truck that records the data for further interpretation by geophysicists and petroleum reservoir engineers.

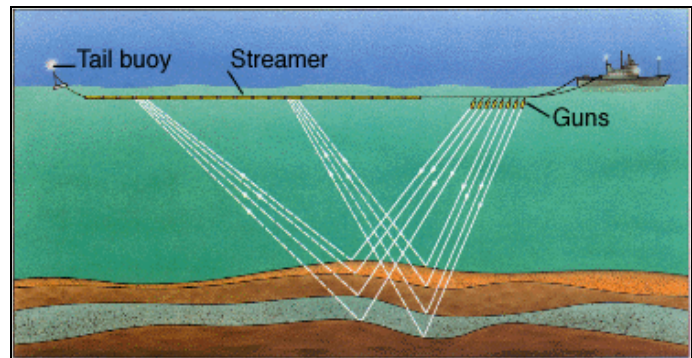
In the past, seismic waves were created using dynamite. Today, most seismic crews use nonexplosive seismic technology to generate the required data. This nonexplosive technology usually consists of wheeled or tracked vehicles carrying special equipment (a vibrator) designed to create a series of vibrations, which in turn creates seismic waves. Other seismic sources include dropped weights and air guns.



**FIGURE 2. 1 Onshore Seismology Using a Vibration Truck as a Seismic Energy Source (Source: modified from DOE 2005a)**

### 2.1.2 Offshore Seismology

Offshore seismic exploration is similar to onshore exploration, but rather than trucks and geophones, a ship is used to convey equipment needed to generate the seismic waves and gather the seismic data, and hydrophones are used to pick up seismic waves underwater (Figure 2.2) (Natural Gas Supply Association 2004a). The hydrophones are towed behind a ship in various configurations, depending on the needs of the geophysicist. Rather than using dynamite or impacts on the seabed floor, the seismic ship uses a large air gun that releases bursts of compressed air under water to create seismic waves that travel through the earth's crust and generate the necessary seismic reflections.



**FIGURE 2. 2 Offshore Seismic Exploration (Source: Schlumberger Limited 2005)**

### **2.1.3 Exploratory Wells and Logging**

Once a specific location has been identified as potentially containing oil and/or gas deposits, one or more exploratory wells are drilled to provide information on the composition of the underground rock layers and their geological and geophysical properties.

Well logging refers to performing tests during or after the drilling process to allow geologists and drill operators to monitor the progress of the well drilling, to gain a clearer picture of subsurface formations, and to identify specific rock layers, in particular those that represent target zones for further exploration. There are many different types of logging; more than 100 different logging tests can be performed to help characterize the composition and characteristics of the different layers of rock through which the well passes. Following interpretation of the logging data, a determination can be made as to whether or not to proceed with the installation of production wells. Logging is also used to monitor the drilling process and to ensure that the correct drilling equipment, materials, and supplies (such as drilling muds), are being used and that drilling is not continued if unfavorable surface or subsurface conditions develop.

Two of the most common types of logging are sample and wireline. Sample logging consists of examining and recording the physical aspects of the rock penetrated by a well. Drill cuttings (rock that is displaced by the drilling of the well) and core samples (intact underground rock samples) may be collected from the exploratory well and physically examined to describe the subsurface rock, determine the position and thickness of the various layers of rock, and estimate (with cuttings) or determine (with cores) the porosity and fluid content of the subsurface rock. Wireline logging consists of lowering a device used to measure the electrical, acoustic, or radiological properties of the rock layers into the downhole portion of the well to provide an estimate of the fluid content and characteristics of the various rock layers through which the well passes.

## **2.2 OIL AND GAS WELL DRILLING**

Today, almost all oil and gas wells are drilled using rotary drilling. In rotary drilling, a length of steel pipe (the drillpipe) with a drill bit on the end is rotated to cut a hole called the well bore. As the well goes deeper, additional sections of drillpipe are added to the top of the rotating drill string. Rotary drilling uses a steel tower to support the drillpipe. If the tower is part of a tractor-trailer and is jacked up as a unit, it is called a mast. If it is constructed on site, it is called a derrick. Both towers are constructed of structural steel and sit on a flat steel surface called the drill or derrick floor; this is where most of the drilling activity occurs. Four major systems comprise an operational rotary drilling rig: the power supply, the hoisting system, the rotating system, and the circulating system.

An operational rig requires a dependable power supply in order for the other rig systems to operate. Power to these systems may be supplied through one or more diesel engines used alone or in conjunction with an electrical power supply.

The hoisting system raises, lowers, and suspends equipment in the well and typically consists of a drilling or hoisting line composed of wound steel cable spooled over a revolving reel. The cable passes through a number of pulleys, including one suspended from the top of the derrick or mast. The hoisting system is used to move drillpipe into or out of the well.

The rotating system includes the turning drillpipe, the drill bit, and related equipment. It cuts the well bore, which may have an initial diameter of 20 in. (51 cm) or more but is usually less. The drill bit is located at the bottom end of the first drillpipe within the rotating system. The drillpipe is rotated by a rotary table located on the derrick floor. The drillpipe consists of heat-treated alloy steel and may range in length from 18 to 45 ft (5 to 14 m); drillpipe length is typically uniform at each individual drilling rig. Before the drillpipe is fully inserted into the well bore, another section of drillpipe is added.

During drilling, the circulating system pumps drilling mud or fluids into the well bore to cool the drill bit, remove rock chips, and control subsurface fluids. Typically, mud is circulated down through the hollow drillpipe. The mud exits the pipe through holes or nozzles in the drill bit, and returns to the surface through the space between the drillpipe and the well bore wall.

### **2.2.1 Drilling Muds**

Drilling muds (also termed fluids) are used during the drilling process to transport rock chips (cuttings) from the bottom of the well up and out of the well bore, where the cuttings are screened and removed, and the separated mud is reused. Drilling muds also act to cool the drill bit, to stabilize the well walls during drilling, and to control formation fluids that may flow into the well.

The most common drilling mud is a liquid-based mud typically composed of a base fluid (such as water, diesel oil, mineral oil, or a synthetic compound), with optional additives such as weighting agents (most commonly barium sulfate), bentonite clay (to help remove cuttings and to form a filler cake on the well bore walls), and lignosulfates and lignites (to keep the mud in a fluid state) (DOE 2005c). Water-based muds and cuttings can be readily disposed of at most onshore locations, and in many U.S. offshore waters offshore disposal occurs as long as applicable regulatory effluent guidelines are met. In contrast, oil-based muds from onshore wells have more stringent land disposal requirements and are prohibited from discharge from offshore well platforms. Synthetic-based muds use nonaqueous chemicals (other than oils) as their base fluid, such as internal olefins, esters, linear alpha-olefins, or linear paraffins. While these fluids have a lower toxicity, undergo more rapid biodegradation, and have a lower bioaccumulation potential than oil-based fluids, they are also prohibited from offshore discharge.

### **2.2.2 Blowout Preventer**

All drilling sites include a blowout preventer. The blowout preventer, which is routinely used in onshore and offshore drilling, is intended to prevent oil, gas, and/or other subsurface liquids (i.e., salt water) from leaving the well and escaping into the atmosphere, onto the ground,

into adjacent water bodies, or overlying waters. At the bottom of a well, there are two fluid pressures. Pressure on fluids in the formation tries to force the fluids to flow from the formation into the well. Pressure exerted by the weight of the drilling mud filling the well tries to force the drilling mud into the surrounding rocks. Under normal operations, the effective weight of the drilling mud is adjusted to exert a slightly greater pressure on the bottom of the well than the effective pressure on the fluid in the rocks, causing the mud to enter the rock and cover the sides of the well and thus stabilize the well. If the pressure on the fluid in the rocks is greater than the pressure of the drilling mud, water, gas, or oil will flow out of the rock into the well. In extreme cases, a blowout occurs where the fluids flow uncontrolled into the well and on occasion violently to the surface. A blowout preventer is a device that is used to close off a well if there is a loss of control of the fluids in the formation. There are a variety of types of blowout preventers. Some close over the top of the well bore, some are designed to seal around the tubular components in the well (such as the drillpipe, casing, or tubing), and some have hardened steel shearing surfaces that actually cut through the drillpipe to seal off the opening.

### **2.2.3 Offshore Drilling**

A major difference between onshore and offshore drilling is the nature of the drilling platform. In addition, in offshore drilling the drillpipe must pass through the water column before entering the lake or seafloor. Offshore wells have been drilled in waters as deep as 10,000 ft (305 m). The following text provides an overview of drilling in offshore environments.

#### **2.2.3.1 Drilling Template**

Offshore drilling requires the construction of an artificial drilling platform, the form of which depends on the characteristics of the well to be drilled. Offshore drilling also involves the use of a drilling template that helps to connect the underwater drilling site to the drilling platform located at the water's surface. This template typically consists of an open steel box with multiple holes, depending on the number of wells to be drilled. The template is installed in the floor of the water body by first excavating a shallow hole and then cementing the template into the hole. The template provides a stable guide for accurate drilling while allowing for movement in the overhead platform due to wave and wind action.

#### **2.2.3.2 Drilling Platforms**

There are two types of basic offshore drilling platforms, the movable drilling rig and the permanent drilling rig. The former is typically used for exploration purposes, while the latter is used for the extraction and production of oil and/or gas.

A variety of movable rigs are used for offshore drilling. Drilling barges are used in shallow (<20 ft [<6 m] water depth), quiet waters such as lakes, wetlands, and large rivers. As implied by the name, drilling barges consist of a floating barge that must be towed from location to location, with the working platform floating on the water surface. In very shallow waters,

these may be sunk to rest on the bottom. They are not suitable for locations with strong currents or winds and strong wave action. Like barges, jack-up rigs are also towed, but once on location three or four legs are extended to the lake bottom while the working platform is raised above the water surface; thus, they are much less affected by wind and water current than drilling barges. Submersible rigs are also employed in shallow waters and, like jack-up rigs, are in contact with the lake bottom. These rigs include platforms with two hulls positioned above one another, with the lower hull acting like a submarine. When being towed to a new location, the lower hull is filled with air and serves to float the entire platform. Once on location, the lower hull is filled with water, and the rig sinks until the legs make contact with the lake bottom. As with the previous movable rigs, use of this type is limited to shallow water areas. Because of their size and relative ease of transport to drill sites, shallow water rigs would be the most likely type of rig that could be employed in the Great Lakes.

The most common movable offshore drilling rig is the semi-submersible rig. It functions in a similar manner to the submersible rig, with a lower hull that can be filled or emptied of water. However, this type of rig does not contact the lake floor but floats partially submerged and is held in place through a number of anchors. This type of rig provides a stable and safe working platform in deeper and more turbulent offshore environments, and when high reservoir pressures are expected. The final type of movable drilling rig is the drillship. These are ships designed to carry drilling platforms great distances offshore and in very deep waters. A drilling platform and derrick are located in the middle of a large, open area of the ship, and the drill is extended through the ship to the drilling template.

When exploratory drilling locates commercially viable oil or gas deposits, a more permanent drilling platform is required to support well completion and oil and/or gas extraction. A variety of such production platforms are used for offshore drilling. Fixed platforms are typically used in areas with water depths less than 1,500 ft (457 m) and would be the most likely type of production platform that would be used in the Great Lakes. These platforms contact the bottom using concrete or steel legs and are either directly attached to, or simply rest on, the bottom. A variety of other production platforms are available for deeper water conditions and would probably not be applicable for use in the Great Lakes.

## **2.2.4 Drilling Techniques**

Several types of drilling techniques are currently employed in oil and gas drilling: straight hole drilling, directional drilling, horizontal drilling, air drilling, and foam drilling. Regardless of the drilling technique, a well is typically drilled in a series of progressively smaller-diameter intervals. Thus, wells typically exhibit their largest diameter at the surface and smallest diameter at the end of the well.

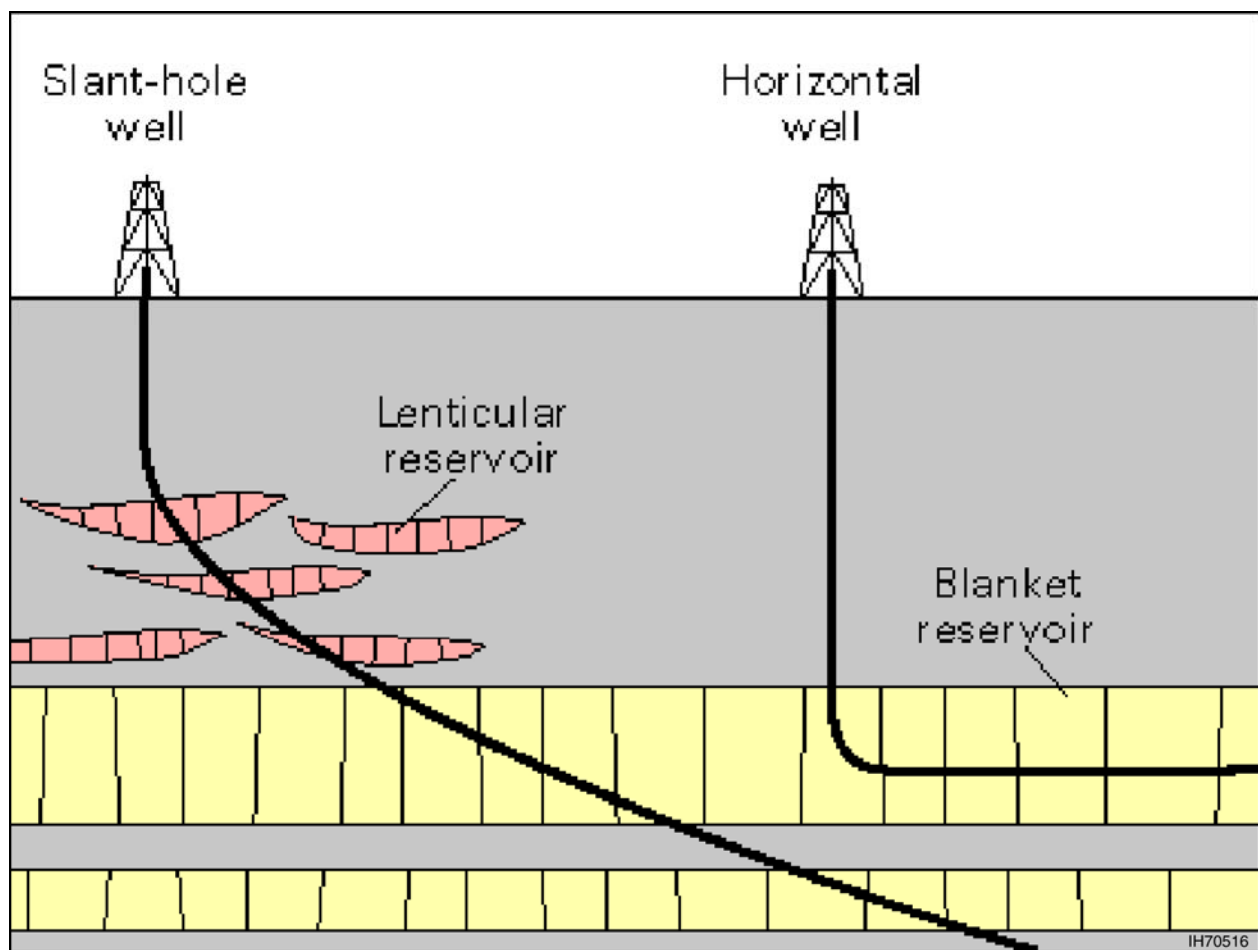
### **2.2.4.1 Straight Hole Drilling**

In straight hole drilling, the well bore is vertical and deviates by no more than 3 degrees anywhere along the well bore, and the bottom of the well deviates by no more than 5 degrees

from the starting point of the well bore at the drilling platform. With straight hole drilling, the drill bit may be deflected if it contacts fault zones or dipping beds of hard rock layers.

#### 2.2.4.2 Directional and Horizontal Drilling

Directional drilling (also termed slant drilling) involves the drilling of a curved well to reach a target formation (Figure 2.3). Directional drilling is employed when it is not possible, practicable, or environmentally sound to place the drilling rig directly over the target area. Directional drilling is especially useful for offshore locations. With directional drilling, it may take several thousand feet for the well to bend from drilling vertically to horizontally.



**FIGURE 2.3 Directional (Slant) and Horizontal Drilling (Natural Gas Supply Association 2004b)**

Horizontal drilling is a form of directional drilling in which a 90-degree turn in the well may be made within a few feet (Figure 2.3). There are three main types of horizontal wells. Short-radius wells have a curvature radius of 20 to 45 ft (6 to 14 m) and can be easily dug out from existing vertical wells. This allows for the development of several wells accessing multiple

reservoirs from a single drilling platform. Medium-radius wells have typical curvatures of 300 to 700 ft (91 to 213 m), with a horizontal extension up to 3,500 ft (1,067 m). Long-radius wells typically have curvatures of 1,000 to 4,500 ft (305 to 1,372 m) and can extend horizontally out to about 15,000 ft (457 m). Long-radius wells are typically used to access offshore deposits (Natural Gas Supply Association 2004).

Horizontal drilling is especially effective in accessing productive formations that are not thick but extend over a large lateral area. Prior to the advent of directional drilling, such formations were either uneconomical or required multiple wells to recover the hydrocarbons. A single horizontal well can contact more of the reservoir and therefore takes the place of several traditional vertical wells. Because the well bore from the surface to the producing formation is drilled only once, a horizontal well generates less waste than several vertical wells (DOE 2005b).

#### **2.2.4.3 Air and Foam Drilling**

Air drilling employs a rotary drilling rig that uses air rather than drilling mud to remove drill cuttings. The drilling rig and operations would be identical to those for a rotary drilling rig, except that there would be no drilling mud circulating system. Instead of a mud, air would be pumped down the drill string and out the drill bit, forcing cuttings up and out of the well bore. While air drilling has a faster penetration rate than mud-based drilling, it does not build up a filler cake and stabilize the walls of the well bore, nor can it control formation fluids. In addition, natural gas flowing into the well can form a flammable mixture with the injected air. Air drilling is typically used in low permeability and porosity reservoir intervals where oil or water are not expected to be encountered during drilling. If (or when) natural gas is encountered during drilling, the gas may be safely combusted at the drill site using a flaring device over a waste containment pit. Foam drilling is similar to air drilling but mixes detergents with the air and a small volume of water to form a foam that is better at removing cuttings and water from the well.

#### **2.2.5 Well Completion**

Once a well has been drilled and verified to be commercially viable, it must be completed to allow for the flow of oil or gas. The completion process involves the strengthening of the well walls with casing and installing the appropriate equipment to control the flow of oil or gas from the well. Casing consists of a stacked series of metal pipes installed into the new well in order to strengthen the walls of the well hole, to prevent fluids and gases from seeping out of the well as it is brought to the surface, and to prevent other fluids or gases from entering the rock formations through which the well was drilled.

Casing extends from the surface to the bottom of the well and is typically steel pipe with a diameter that may range from 4.5 to 36 in. (11 to 91 cm). Casing with a diameter slightly smaller than that of the well hole is inserted into the well, and a wet cement slurry is pumped between the casing and the sides of the well. Casing is installed as the well is progressively drilled deeper. The top interval of the well, extending from the surface to a depth below the lowermost drinking water zone, is the first to be completed, being cemented from the surface to



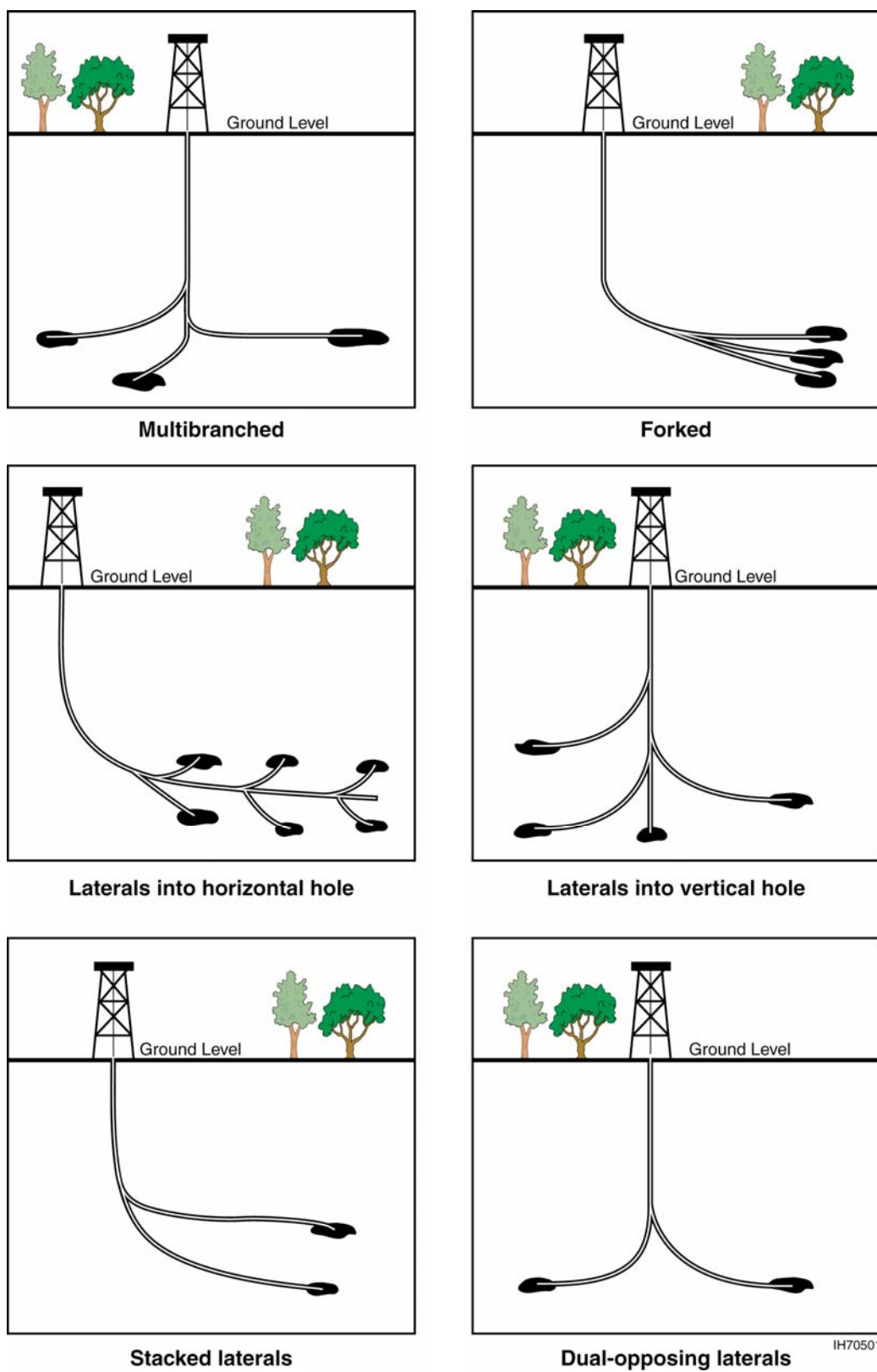
below the drinking water zone. Next, a smaller diameter hole is drilled to a lower depth, and then that segment is completed. This process may be repeated several times until the final drilling depth is reached.

Another aspect of well completion is the selection of an appropriate intake configuration for the well. Intake configurations are designed to permit the flow of oil or gas into the well, and the selection of a particular intake type will depend on the nature of the formation surrounding the intake portion of the well. Well completion also involves the installation of an appropriate wellhead. A wellhead is the permanent equipment mounted at the opening of the well that is used to regulate and monitor oil or gas extraction from the well. The wellhead also prevents oil or gas leakage from the well and blowouts due to high-pressure formations associated with the well. For wells with sufficient pressure for the oil or gas to reach the surface without assistance, the wellhead will include a series of valves and fittings to control the flow. Gas wellheads in the Canadian waters by Lake Erie are located on the lake bottom because of winter ice and navigational concerns. Such wellheads would likely be used for any offshore wells in U.S. waters of the Great Lakes.

Most modern (or recently drilled) onshore U.S. oil wells do not have enough internal pressure for the oil to flow to the surface. For such oil wells, lifting equipment or well treatment is used to bring the oil to the surface. Lifting equipment typically involves the use of some type of mechanical surface or downhole pump. Well treatment involves the injection of acid, water, or gases into the well to open the formation and allow oil to flow more freely through it and into the well. For some oil wells, a compressed gas (often natural gas collected from the oil well) is injected into the well. This gas dissolves into the oil, forming bubbles that lighten the oil and bring it to the surface. For wells in limestone or carbonate formations, acid may be injected under pressure to dissolve portions of the rock and thus create spaces that enhance the flow of oil. Fracturing involves the injection of a fluid that cracks or opens up fractures in the oil-bearing formation. In some cases, propping agents may be added during the injection. Propping agents are materials that act to prop open newly widened fractures; these agents can consist of sand or glass beads. While well treatment has been used more often for oil wells, it has also been used to increase extraction rates in gas wells.

## **2.2.6 Drilling and Production Site Size**

The oil and gas industry is addressing the issue of habitat loss by reducing the footprint of drilling and production facilities (DOE 1999; Arscott 2004). Facility footprints have been reduced through the use of laterals drilled from individual wells. Laterals are short, horizontal branches drilled from a single well bore. With current technology, several laterals may be drilled off the main vertical well bore to reach individual reservoirs. In these cases, the main well bore is drilled once, followed by the drilling of several smaller-diameter lateral well bores (Figure 2.4). With this type of drilling, only a single surface drilling location may be needed to access multiple reservoirs, and/or a greater portion of a single reservoir, thus greatly reducing the amount of surface disturbance and the total volume of drilling wastes that would be generated if multiple surface wells were drilled. For example, BP's Alaska Kuparuk field uses a 55-acre (22-ha) facility as an operations base compared with a 1,000-acre (405-ha) site providing



**FIGURE 2.4** Examples of the Types of Lateral Well Bores That May Be Drilled from a Single Location to Access Multiple Reservoirs

similar facilities in the original Prudhoe Bay field. If the entire Prudhoe Bay oil field were built with today's technology, its footprint would be 64% smaller than its current size. The area impacted by drilling pads would be 74% smaller; roads would cover 58% less surface area; and oil and gas separating facilities would take up 50% less space. Today, new production pads are up to 70% smaller than the original Prudhoe pads, and spacing between wellheads has been reduced dramatically.

### 2.2.7 Post-Production Treatment and Storage

Once the oil or gas reaches the wellhead, it enters into a steel, plastic, or fiberglass flowline and is directed to separation and storage equipment. For multiple wellheads, separation and storage may occur at each well or at a central processing unit. Oil wells often produce natural gas and water as well as oil. If there is natural gas and water vapor flowing through the flowline, a hydrate may form that blocks the flowline. To prevent this, heaters can be installed on the flowlines, or chemicals such as glycol or methanol can be added to the produced fluids to prevent hydrate formation. Natural gas produced at a well often needs to be processed prior to its sale. Impurities in the gas are removed by using any of a variety of gas conditioning processes in the field. Gas conditioning often involves the use of a dehydration system to boil off water and the gaseous impurities. In such systems, triethylene glycol is circulated through a boiler unit that boils off the water and gas impurities, producing methane and other volatile and semivolatile organic compounds (VOCs and SVOCs, respectively) such as benzene, toluene, ethyl benzene, and xylenes, which may then be vented to the atmosphere (DOE 1999).

Most oil wells produce saltwater along with gas bubbling out of the oil. These materials are separated in a metal tank (separator) that has an inlet for fluids from the flowline and separate outflows at different levels for each of the separated fluids. Separators may be horizontal or vertical (Figure 2.5) and may be either two-phase (separates gas from liquid) or three-phase (separates gas, oil, and water).



**FIGURE 2.5 Horizontal and Vertical Gas and Oil Separators (Source: JL Bryan Equipment 2005)**

Oil from the separator goes through another flowline and into a stock tank for storage until the oil is transferred to a tanker truck or into a pipeline system and leaves the site. Stock tanks are made of bolted or welded carbon steel and range in size from 90 to several thousand barrels of oil. A minimum of two and usually three or four stock tanks are connected by pipe in a tank battery for sequential filling (Figure 2.6).



## 2.3 WASTE MANAGEMENT

Wastes generated during oil and gas exploration and production fall into four general categories: used drilling muds and drill cuttings, produced water, low-volume “associated wastes,” and other wastes.

**FIGURE 2.6 Tank Battery (Source: Eastern Energy Corporation 2003)**

### 2.3.1 Drilling Muds and Cuttings

Drilling rigs that use drilling mud will generate a large volume of used drilling mud. Drilling muds that are oil- or synthetic-based are typically recycled, although over time the oil or synthetic materials may degrade and render the mud unusable for further drilling. Most water-based muds are disposed of after the completion of drilling although they can be managed to allow the water to be recycled.

Drill cuttings are bits of rock that are ground up during the drilling process and brought to the surface with the drilling mud as the well is being drilled. Most drill cuttings are managed through disposal, although some are treated and beneficially reused. In some circumstances, drill cuttings can be beneficially reused for stabilizing road surfaces, as landfill cover material, or as a construction material. For example, oily cuttings have been used to provide the same service as tar-and-chip road surfacing, although not all regulatory agencies allow for such a reuse (DOE 2005d). For reuse, the hydrocarbon content, moisture content, salinity, and clay content of the cuttings are evaluated to determine suitability of the cuttings for a specified reuse. Some cuttings may undergo washing to remove dissolved salts prior to reuse, with the wash water being handled in the same manner as produced water.

Most U.S. offshore platforms discharge cuttings from water-based and synthetic-based systems, as well as water-based muds. Cuttings from oil-based muds, as well as oil-based and synthetic-based muds, must be transported to shore for disposal at an onshore commercial facility.

At most onshore well sites in the United States (with the exception of Alaska), drilling wastes are managed on site by burial in pits or landfills, or through land application or other biological treatment. For some types of wastes, or at particularly sensitive locations, these

disposal methods are not permitted, requiring the drilling wastes to be transported off site for disposal at a commercial disposal facility or municipal landfill.

### **2.3.2 Produced Water**

In subsurface formations, naturally occurring rocks are generally permeated with fluids such as water, oil, or gas (or some combination of these fluids). Reservoir rocks normally contain both petroleum hydrocarbons (liquid and gas) and water. Extraction of oil or natural gas from reservoirs also generates produced water. Produced water is any water that is present in a reservoir with the hydrocarbons and is brought to the surface with the crude oil or natural gas. When hydrocarbons are extracted, they are brought to the surface as a produced fluid mixture. The composition of this mixture is dependent on whether crude oil or natural gas is being produced and generally includes a mixture of either liquid or gaseous hydrocarbons, produced water, dissolved or suspended solids, and any injected fluids and additives that may have been placed into the formation as a result of E&P.

As reservoir pressure declines over time, additional water is often injected into the reservoirs to help force the oil to the wells. This process is known as enhanced oil recovery. Both formation and injected water are brought to the surface along with the hydrocarbons and as the reservoir becomes depleted, the amount of produced water increases as the reservoir fills with the injected water. Produced water is usually very salty and may contain residual hydrocarbons, heavy metals, naturally occurring radionuclides, numerous inorganic species, suspended solids, and chemicals used in hydrocarbon extraction.

At the surface, produced water is separated from the hydrocarbons and treated to remove as much oil as possible (see Section 2.2.6). At offshore facilities, this treated water is generally discharged into the sea under the authority of a permit issued by the EPA. At most onshore locations, produced water cannot be discharged and is therefore injected underground either for enhanced oil recovery or for disposal. In some parts of the western United States, produced water can be discharged if it is not too salty and it can be beneficially reused. In recent years, researchers have been exploring ways to treat salty produced water for potable or agricultural uses.

### **2.3.3 Associated Waste**

The process of producing, treating, storing, and transporting crude oil and natural gas generates low volumes of a variety of wastes, such as sludges, scales, produced sand, and other process-related wastes. These wastes, referred to as “associated wastes,” make up less than 1% of the total volume of waste generated by oil and gas exploration and production (EPA 1987). These wastes are managed in much the same way as other operational wastes.

### 2.3.4 Other Wastes

Waste soils may also be generated as a result of oil and gas activities. These would include soils contaminated by releases of crude oil, produced water, or other materials. Contaminated soils are frequently managed along with other operational wastes.

As previously described (Section 2.2.6), oil and gas separators are used to separate produced water and gases from the extracted oil. Disposal of the produced water is conducted in the manner described previously. The methane, VOCs, and SVOCs removed from extracted natural gas are vented directly into the atmosphere. These air emissions are often reduced through the use of additional separators and condensers to capture the methane, VOCs, and SVOCs, thereby reducing the amounts of these materials that are vented to the atmosphere. In addition, adjusting the glycol circulation during dehydration optimizes the extraction of water and other impurities (DOE 1999).

### 2.3.5 Disposal Alternatives

#### 2.3.5.1 Disposal in On-Site Pits and Landfills

Waste management using on-site disposal involves the burial of the drilling muds in man-made or natural pits or landfills. Burial is the most common onshore disposal approach for disposing of drilling muds and cuttings (DOE 2005e). In most U.S. onshore drilling operations, cuttings are separated from the drilling muds and sent to a pit called the reserve pit located near the drilling rig (Figure 2.7). Such pits are typically open to the atmosphere and also receive wash water from the drilling rig as well as storm water. Liners are almost always required, and their siting and construction require careful consideration of a variety of factors, including surface topography, underlying geology, nearby surface waters, and underlying aquifers. After completion of drilling activities, any hydrocarbon products floating on top



**FIGURE 2.7 Oil Field Waste Pits**  
(Source: USFWS 2001)

of the pits as well as any water or other liquids are removed for disposal. The remaining materials are evaluated to ensure that they do not exceed regulatory limits for pit disposal. The materials that do not exceed regulatory limits are covered in place with clean soil, the surface is graded to prevent water accumulation, and the area is revegetated to control erosion and runoff. Drilling wastes are also disposed of in engineered landfills. Depending on the applicable regulatory requirements, these landfills will typically have either clay or synthetic liners, and wastes placed into the landfill are covered with clean soil or other cover material on a regular interval (e.g., daily or weekly).

### **2.3.5.2 Disposal Using Land Application**

Land application uses the soil's natural microbial population to metabolize, transform, and assimilate waste constituents in place. Land spreading and land treatment are often used interchangeably to describe the one-time application of wastes to the soil surface (DOE 2005i). Land spreading involves only a one-time application of the drilling wastes, thus limiting the potential for buildup of salt, hydrocarbons, and other waste-related materials. Land farming refers to the repeated application of wastes to the soil surface. It often includes tilling the drilling wastes into the soil and adding nutrients (fertilizer) to enhance microbial action (DOE 2005i). Many states regulate the salt, hydrocarbon, and metals content of wastes that can be disposed of by land application.

### **2.3.5.3 Disposal Using Bioremediation**

Bioremediation is similar to land application in that it also relies on microorganisms to degrade hydrocarbon-contaminated drilling muds and cuttings (DOE 2005j). Bioremediation, as used here, accelerates the microbial degradation process through active manipulation of temperature, oxygen, moisture, and nutrients within the materials undergoing bioremediation. Common forms of bioremediation include composting and the use of bioreactors. Composting involves the addition of bulking agents (such as straw) to increase porosity, enhance aeration, and increase water-holding-capacity of the materials being composted, and the addition of fertilizer (such as manure) to provide nutrients for increased microbial activity. Bioreactors work in the same manner as composting or land application, but use open or closed vessels or impoundments that allow for increased control of temperature, moisture, and oxygen, thus enhancing microbial activity.

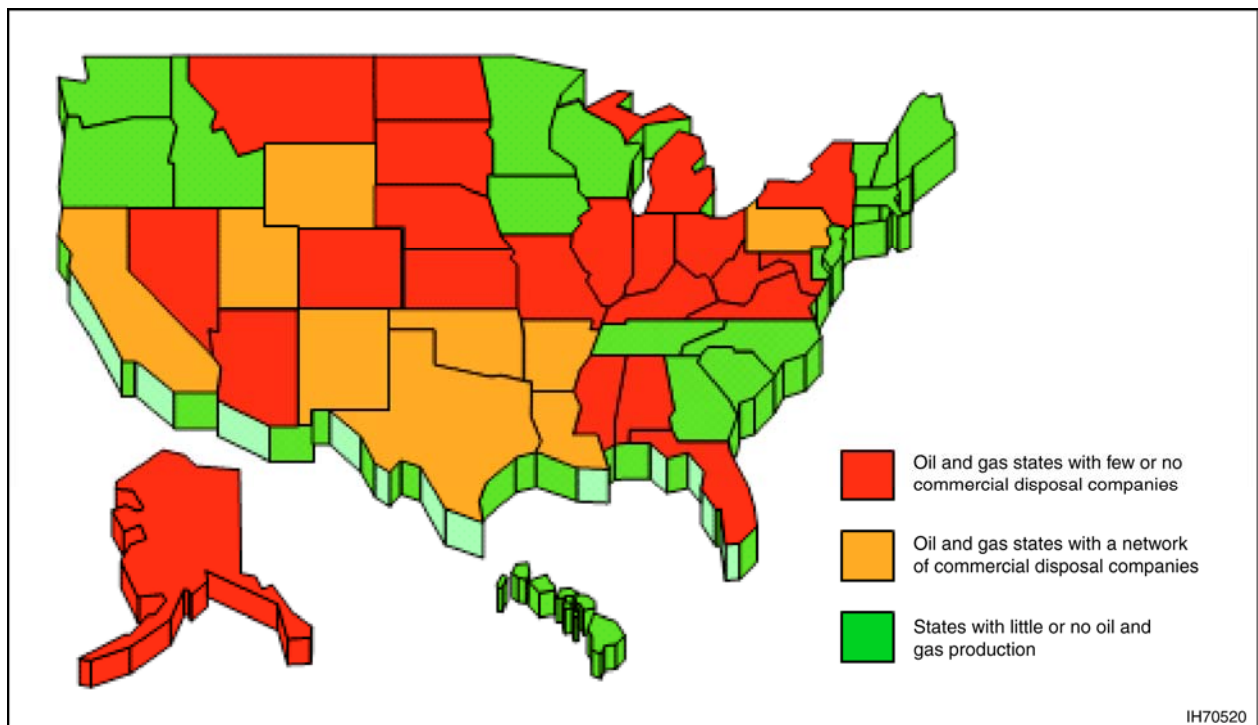
### **2.3.5.4 Off-Site Disposal**

In contrast to on-site waste disposal, drilling wastes are also managed through disposal at licensed off-site commercial facilities or at municipal landfills if the landfill acceptance requirements are met. Commercial facilities use a variety of approaches for disposing of the oil and gas wastes, including pits and landfills, some form of on-site treatment (e.g., biological, chemical, or thermal), subsurface disposal, and landfarming (DOE 2005f). Examples of inappropriate wastes for on-site disposal may include saltwater muds or very oily cuttings. Examples of locations that are not appropriate for on-site burial or land application include areas with high seasonal water tables, wetlands, or tundra (DOE 2005f). At least nine oil- and gas-producing states (Figure 2.8) (Veil 1997) have commercial disposal companies that exclusively handle oil field wastes. Many more oil- and gas-producing states have few or no disposal companies dedicated to oil and gas industry waste. In those states, oil field wastes must be sent to other off-site commercial landfills or out of state. As recently as 1997, only Pennsylvania among the Great Lakes states had commercial off-site disposal facilities for oil and gas wastes.



### 2.3.5.5 Underground Injection

In areas lacking local waste management infrastructure (such as Alaska), drilling wastes are often disposed of through injection into underground formations. Underground injection involves the grinding or processing of the drilling waste solids into small particles, then mixing them with water or some other liquid to make a slurry and injecting the slurry into an underground formation at pressures high enough to fracture the rock. The process referred to here as slurry injection has been termed fracture slurry injection, drilled cuttings injection, cuttings reinjection, and grind and inject (DOE 2005g).



**FIGURE 2.8 Off-Site Commercial Dedicated Oil and Gas Waste Disposal Facilities, 1997 (Source: Veil 1997)**

The two common forms of slurry injection are annular injection and injection into a disposal well (Figure 2.9). With annular injection, the waste slurry is injected through the space between two sections (strings) of casing (this space is known as the annulus), with the slurry entering the formation at the lower end of the outermost casing string. Injection into a disposal well involves injection into either a section of the drilled hole that is below all casing, or to a section of the casing that has been perforated with a series of holes at the depth of an injection formation.

When the slurry is ready for injection, the underground formation is prepared to receive the slurry. First, clear water is rapidly injected to pressurize the system and initiate fracturing of the formation (DOE 2005g). When the water is flowing freely at the fracture pressure, the slurry



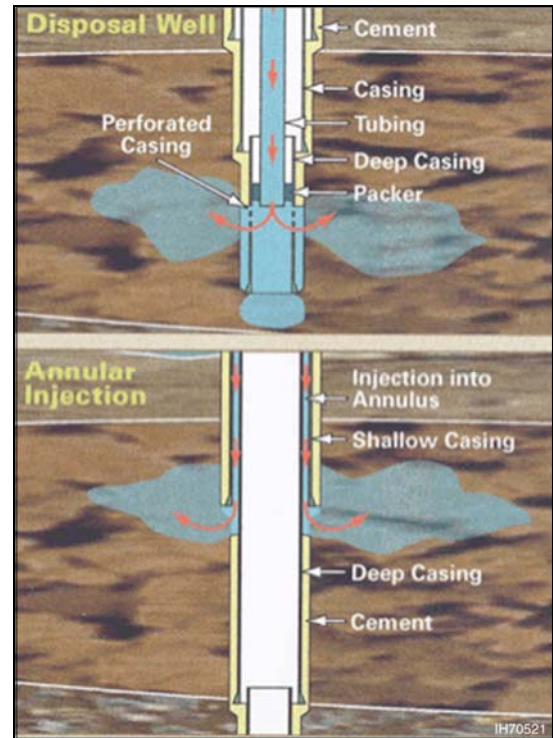
is introduced into the well. Slurry injection continues until an entire batch of material has been injected. Additional water is then injected to flush solids from the well bore, and pumping is discontinued. The pressure in the formation gradually declines as the liquid portion of the slurry bleeds off over the next few hours, and the solids become trapped in place in the formation. Slurry injection can be conducted as a single continuous process or as a series of smaller-volume intermittent cycles. On some offshore platforms, where drilling occurs continually and storage space is inadequate to operate in a daily batch manner, injection occurs continuously as new wells are drilled. However, most injections occur intermittently (DOE 2005g).

The most common problems with slurry injection are operations related. These problems may include the plugging of the casing or piping by solids that have settled out during or following injection; and the excessive erosion of casing, tubing, and other system components caused by pumping solids-laden slurry at high pressure. Environmental problems associated with slurry injection include unanticipated leakage to the environment (the surface of the seafloor in the case of offshore wells). Such leakage events are most likely due to a fracture that has moved up and away from the injection point and intersected a natural geologic fault or fracture, or a different well that had not been properly cemented. Because they are under high pressure, the injected fluids seek out the pathway of least resistance. Thus, if a crack in a well's cement job or geological fault is present, the fluids may preferentially migrate upward and reach a shallower formation (e.g., a drinking water aquifer), the land surface, or the seafloor.

Two commercial injection facilities manage a large portion of oil and gas industry wastes in the U.S. Both are located in Texas in areas with favorable geologic settings. One facility injects wastes into fractured limestone beds flanking salt dome deposits, and the other injects wastes into solution mined salt caverns. The viability of underground injection in other areas will depend upon local geologic conditions.

### 2.3.5.6 Disposal in Salt Caverns

Underground salt deposits, occurring as salt domes or bedded salt formations, are found throughout the continental United States (DOE 2005h). Salt domes are large, finger-like projections of nearly pure salt that have risen to near the surface, while bedded salt formations consist of multiple layers of salt separated by layers of other rocks. Salt deposits may occur at



**FIGURE 2.9 Annular and Disposal Well Slurry Injection (Source: DOE 2005f)**

depths of 500 ft (152 m) to more than 6,000 ft (829 ft) below the surface. Large salt caverns have been used for decades to store natural gas, crude oil, and other hydrocarbon products. During the 1990s, several companies in Texas received permits to dispose of drilling waste and other oil-field wastes in salt caverns (DOE 2005h).

Drilling wastes are brought to the cavern site where they are blended with water or brine to make a slurry. Drilling wastes suitable for disposal in caverns include drilling muds, drill cuttings, produced sands, tank bottom sediment, contaminated soil, and completion wastes. Grinding equipment may be used to reduce particle size. The waste slurry is then pumped into the caverns. Inside the cavern, the solids, oils, and other liquids separate into distinct layers: solids sink to the bottom, the oily and other hydrocarbons float to the top, and brine and other watery fluids remain in the middle (DOE 2005h).

Salt formations are found beneath portions of the Great Lakes Basin, but no disposal of wastes has occurred in these formations within the Basin. As of 2005, in the United States, only Texas had issued permits for the disposal of oil field wastes in salt caverns. Louisiana adopted cavern disposal regulations in May 2003 but has not yet permitted any disposal caverns. Several disposal caverns are operated in Canada, while in early 2004, Mexico announced that it was developing regulations for disposal of oil-based muds and cuttings in salt caverns (DOE 2005h).

## **2.4 WELL ABANDONMENT**

If well logs determine that there is insufficient hydrocarbon potential to complete an exploratory well, or after production operations have drained a reservoir, the well must be plugged and abandoned. Following removal of production equipment, onshore and offshore wells are plugged and abandoned in a similar manner, although different regulatory bodies have their own requirements for plugging operations. Typically, cement plugs are placed and tested across any open hydrocarbon-bearing formations, across all casing shoes, across freshwater aquifers, and possibly several other areas near the surface, including the top 20 to 50 ft (6 to 15 m) of the well bore. This is accomplished by pumping a cement slurry to the desired location within the well bore. For plugging at locations above the well bottom hole (such as at aquifer locations), bridge plugs are used to prevent the cement from falling into the well bore. The bridge plug is set below the well section to be plugged, and cement is pumped on top of the plug..

At onshore locations, after the well has been plugged the casing is cut below the ground surface and a steel plate is welded to the top of the casing. The area around the sealed well is then backfilled with clean fill and a marker is installed indicating the presence of an abandoned well. For abandoned offshore wells, after the well has been plugged and abandoned the casing and production platform supports are cut at or below the bottom surface and the production rig is often toppled where appropriate and permissible to provide an artificial reef.

## 2.5 PIPELINE CONSTRUCTION

Pipelines are typically used to transport oil and natural gas to storage, processing, or distribution facilities. The construction of pipelines differs considerably between offshore and onshore.

Offshore pipelines are typically constructed by assembling pipeline sections on a barge (the lay barge) and lowering the pipeline string to the lake or sea bottom as the barge follows the pipeline route. Pipelines that are greater than about 8 in. (20 cm) in diameter and are installed in water depths less than 200 ft (61 m) are typically buried to a depth of at least 3 ft (1 m) below the mudline. Burial reduces the potential for pipeline movement due to high currents or storms and protects the pipelines from damage from anchors, fishing gear, and boat traffic.

Offshore pipeline burial typically involves the use of a jetting sled to dig a trench for the pipeline. Jetting sleds have high-pressure water jets that are directed downward and as the sled is pulled along the seafloor by the lay barge the water jets dig the trench while the sled guides the pipeline into the trench. In areas where solid bedrock is present at the bottom of the surface water body, some type of rock-cutting tool may be required to augment trenching capabilities of the high-pressure water jets.

Onshore pipeline construction requires the removal of vegetation and other surface features (such as large boulders) that may interfere with construction equipment. As the surface is cleared, sections of pipe are laid along the route in a process called stringing. Individual pipe sections may be up to 80 ft (24 m) in length and configured (pipe thickness and coating materials) specifically to that portion of the route. Next, a trench is dug alongside the laid out pipe. Trench depths are typically 5 to 6 ft (1.5 to 2 m) below the ground surface, but must provide a depth sufficient to ensure that the buried pipeline is at least 30 in. (76 cm) below the surface of the ground.

Next, the pipeline sections are welded together, and if needed, bent slightly to fit the contours of the trench. The pipeline is then lowered into the trench. Then water under high pressure (hydrostatic testing) is run through the pipeline to identify any leaks that may be present. Additional tests, such as x-ray examination of welds, are also conducted. If no leaks are found, the pipeline is ready for use; otherwise, those sections with leaks are repaired or replaced, and hydrostatic testing is repeated. Finally, the trench is backfilled with soil.

Two approaches are typically used if the pipeline must cross a river or stream. In one approach, a trench is dug into the stream bottom to receive the pipeline. That portion of pipe located in the crossing is fitted with a concrete casing that serves to maintain the position of the pipeline on the stream bottom and to provide added protection. The other approach involves the excavation of a tunnel beneath the river through which the pipe would pass. This latter approach is also typically used for crossing roads.

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